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METHODS FOR IMPROVING DEPTH PERCEPTION IN HMDS

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ABSTRACT

Head mounted display systems typically present imagery to the user focused either at infinity (collimated light into the eyes), or alternatively at some nominal finite distance in the order of 11 - 18 feet (diverging light into the eyes). When the imagery presented by an HMD is focused at a finite distance, the right and left eyes are sometimes intentionally set to converge to that same distance. Alternatively, the eyes are often left viewing parallel to one another. In some HMDs the user is permitted to select his or her own preferred focus distance. There appears to be an advantage in improving depth perception in an HMD simulation environment by altering in real time the focus or apparent object distance to match the distance of the principal object or objects being viewed at that time by the user. An eye tracker may be employed to determine where in the scene the user is looking, and the data is fed back to the computer to perform, as appropriate, the refocusing task based on the known distance of the object being looked at. Further realism improvement is likely by changing the convergence as well. This paper will discuss the relative merits of altering the accommodation and convergence as well as the means for accomplishing the refocusing task in the HMD viewing optics rapidly, in real time, and without otherwise altering the image quality or magnification. The net goal is to improve the overall realism of the simulation to the user.

INTRODUCTION

Head-mounted displays (HMDs) have found widespread use in a variety of applications. Their application for pilot training has been especially successful because they are much less expensive and less dangerous than actual flying, and far less expensive to implement than large dome simulators.

To achieve the best results in training, the training environment presented by the HMD should be as close as possible to the actual environment experienced by the pilot. One of the most important improvements in HMDs is the accurate simulation of depth and three-dimensional images.

The need for high quality three-dimensional imaging in flight simulation and other applications has driven the development of various technologies (Okoshi, 1980)). Many of these technologies are fairly complex (i.e. Williams, 1988) and are still far from implementation. As a result the only technique currently being used in such applications is dichoptic (separate image to each eye) presentation of binocular disparity. This paper describes preliminary efforts at OPTICS 1 to improve the realism of HMDs and to determine the merits and viability of adjusting in real time the accommodation or apparent object distance as well as the convergence in an HMD.

SPECIFICATIONS AND REQUIREMENTS

The HMD specifications to which we will work are summarized in Table 1 below. These data represent our best effort at describing a viable and achievable HMD implementation with good performance.

Paper presented at the RTO HFM Workshop on "The Capability of Virtual Reality to Meet Military Requirements", held in Orlando, USA, 5-9 December 1997, and published in RTO MP-54.

Parameter	Specification
Full diagonal field of view	40 degrees
Exit pupil diameter	7mm minimum, 10mm goal
Eye relief	25.4mm minimum
Exit pupil location	Always at eye pupils
Interpupillary distance, nominal	62 mm
Range for interpupillary distance	52 – 72 mm
Distortion	3% maximum
Image blur within horizontal inscribed circle	2.5 minutes of arc maximum
Image blur to corner	3.5 minutes of arc
Spectral band	Visual
Spectral weighting	Photopic eye response
Minimum accommodation distance	15 inches
Maximum accommodation distance	Infinity
Convergence at infinity	Zero
Convergence at 15 inches	9.3 degrees
Speed of change in accommodation	<0.6 seconds
Magnification change over accommodation range	4% maximum
Eye tracker	Yes

Table 1.

VISUAL EFFECTS AND MERITS OF VARYING ACCOMMODATION AND CONVERGENCE TO ENHANCE REALISM

Depth Perception in a Natural Environment

The human mind uses a wide variety of clues to determine distance and depth. These clues include angular extent of an object, occlusion by other objects, perspective, convergence, and accommodation. Each of these clues need to be carefully considered in the complete implementation of an HMD system. However, only convergence and accommodation can be addressed in the physical and optical design of an HMD system, so these will be the only topics addressed in this paper.

Convergence is the rotation of the eyes towards an object. As a person looks at an object, the eyes rotate so that the object is imaged onto the fovea of the retina which is the small region of highest visual acuity. This rotation means that the centerlines of the eyes intersect at the object. Convergence is measured by the total included angle between the eye's centerlines. This angle between the eyes is one of the most important visual clues to depth. Unfortunately for HMD designers, this angle is a function of the user's interpupillary distance or IPD.

Accommodation is the refocusing of the eyes to the distance of the object being viewed.

In a natural viewing environment, accommodation and convergence work together to aid in determining distance. The distance at which the eyes are focussed is the same as the distance at which the eyes' centerlines intersect.

Depth Perception in an Artificial Environment

HMD designers must try to approximate the natural environment depth perception as well as possible. However, they are subject to several constraints which should also guide their design considerations. First, because of the inter-relationship between the IPD and the convergence angle, an exact match between accommodation distance and convergence angle is possible for only a small set of cases. Second, because objects of varying distances may be represented on the same viewing screen, some mismatch between accommodation distance and represented distance is inevitable.

Two measures describe the degree to which an HMD differs from the natural viewing environment. The first measure is called "accommodation error" and is a measure of the difference between the distance at which the eye is focussed and

the distance at which the object is represented. The second measure is called "convergence error" and is a measure of the difference between the convergence angle required by the displayed objects distance and the convergence angle presented by the HMD.

Many difficulties occur when the convergence error and accommodation error are too large. These difficulties include loss of realism, headaches, double vision, blurred vision, and, in extreme instances, even nausea. For small errors, these difficulties tend to ease as the duration of HMD use increases. For larger errors and longer duration of HMD use, however, these difficulties can persist even after the used of the HMD.

Determining the acceptable errors in accommodation and convergence angle is an active area of research. The HMD design community should probably never expect to obtain definitive, universally applicable results for the acceptable errors for several reasons. First, this research is, by definition, very subjective and dependent on the particular experimental parameters. Second, different situations will have different acceptable errors; the requirements on a HMD for a military flight simulator are very likely to be different from those of an inexpensive video game. Third, everyone's visual system is different; a wide variety of common eye conditions can cause people to be unusually sensitive or unusually lax in their tolerance to convergence error or accommodation error. Finally, people have a wide variety of tolerances to non-ideal situations, due merely to their personalities, moods, and temperaments.

To precisely investigate visual effects and merits of varying accommodation and convergence, it is important to precisely define our terms. Accommodation error is

$$A = 1/s_o - 1/s_f,$$

where s_o is the object distance to be represented, s_f is the distance at which the HMD is focussed, and A is the accommodation error. Accomodation error is usually expressed in diopters. (1 diopter = 1/meter) The ideal convergence angle is

$$CA_{ideal} = IPD/s_o,$$

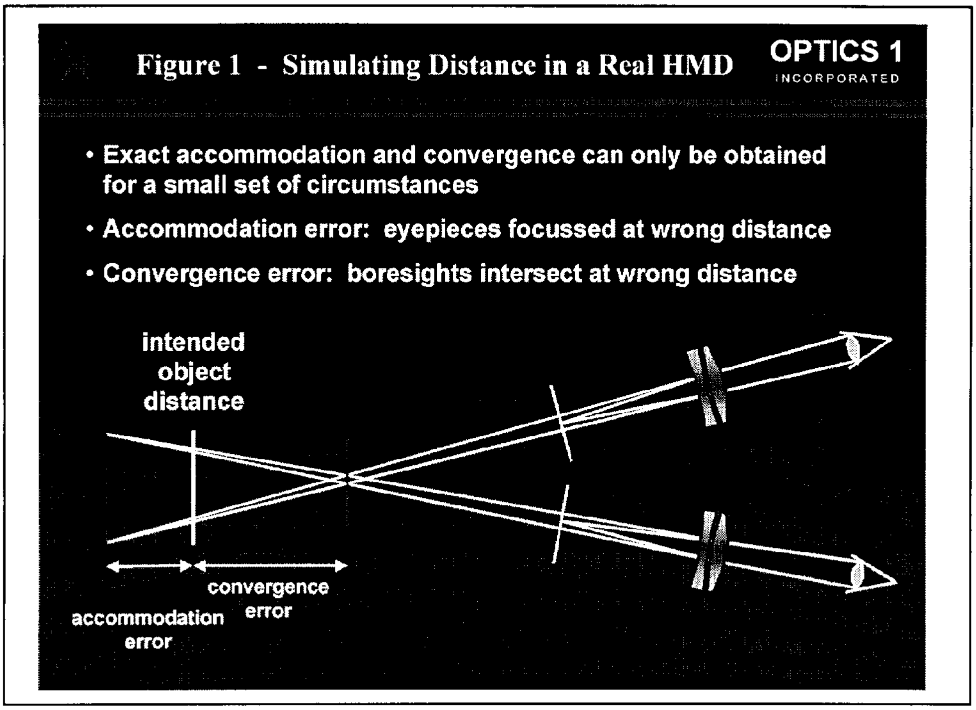
where IPD is the interpupillary distance, and CA_{ideal} is the ideal convergence angle. The convergence angle error is

$$\square_{CA} = CA_{real} - CA_{ideal},$$

where $\square_{CA}$ is the convergence angle error, and CA_{real} is the convergence angle presented to the user. Convergence error can be expressed in either degrees or prism diopters. (1 prism diopter = 0.01 radian = 0.57 degrees).

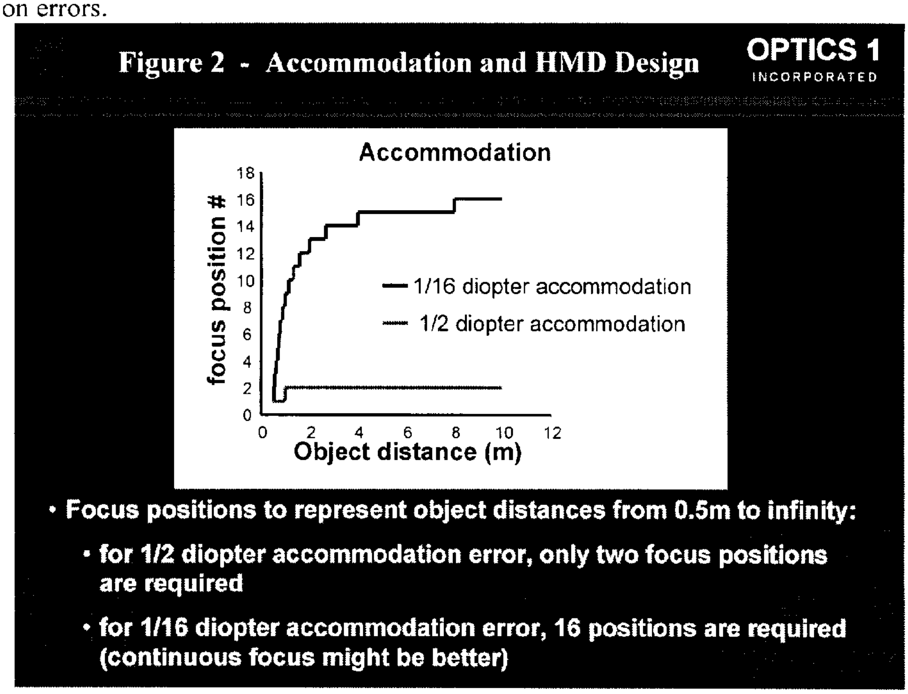
Nevertheless, it is helpful to investigate the requirements of an HMD for various assumptions of convergence angle error and accommodation error.

Figure 1 shows how the convergence and accommodation interrelate, and how errors in both can happen.



The top line in the figure shows that, for an acceptable accommodation error of 1/16 diopter, 16 focus positions would be required to represent the range of object positions; for object positions between 0.5m and 2m, a near-continuum of positions is required. The bottom line on the figure shows that, for an acceptable accommodation error of 1/3 diopter, only three focus positions are required. Figure 3 shows the required convergence angles for object distances from 0.5 meter and above. The two curves are for convergence errors of 1.5 degrees and 0.2 degrees.

Figure 2 shows the required focus positions for object distances from 0.5m to infinity for two acceptable accommodation errors.



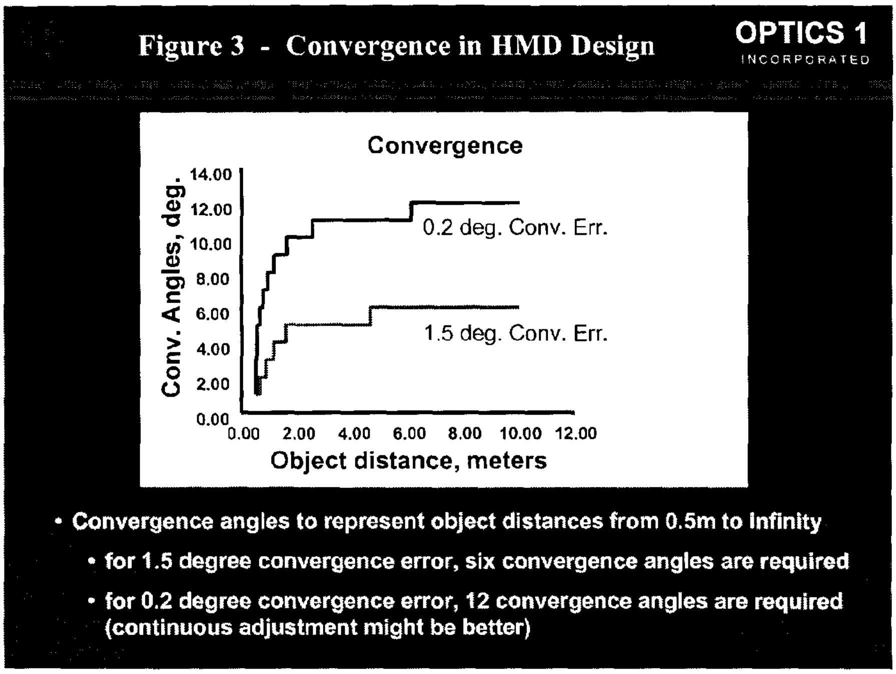


Figure 3 - Convergence in HMD Design

ACCOMMODATION METHODS

A wide variety of accommodation methods are feasible. These methods include, in no particular order:

1. Translating the lens assembly
2. Translating the display device
3. Translating a sub-group of lens elements
4. The Alvarez asphere, bifocal/multifocal lenses
5. Bifocal or multifocal lenses
6. Liquid filled lens
7. Liquid crystal lens
8. Adaptive optics

1. Translating the lens assembly relative to the display device changes the accommodation distance from infinity to a closer image distance. Presenting images at infinity and at 0.5m requires moving the lens assembly about 3mm for a 35mm focal length lens. This method of accommodation has several advantages, most importantly, it is easy to implement. This method has some disadvantages, too: it requires moving parts. A potential disadvantage is that the exit pupil location where the eye is located may move causing vignetting or clipping of light at off axis field positions.

2. Translating display device switches from a distant image distance to a close image distance by moving the display device from the back focus of the lens to a position inside the back focus. This is similar to translating the lens assembly. It has the advantage of not changing the stop position if the viewing optics is designed to be "telecentric" at the display. Unfortunately, it has a serious disadvantage in that display mounts are usually fairly complex and would be difficult to move.

3. Translating a sub-group of lens elements within the lens assembly switches from a distant image distance to a close image distance by changing the lens assembly's focal length much as in a zoom lens. This method has the advantage that it can be easy to implement and that the moving mass can be very small. Its disadvantages include more complex lens housing and the inherent disadvantages of moving parts.

4. The Alvarez asphere switches from a distant image distance to a close image distance by moving special aspheric surfaces perpendicular to the optical axis. A similar method was used in the autofocus mechanism in the Polaroid Spectra camera. This method has several advantages: only a small mass must be moved, the center of mass does not change, and only a small motion is required. Further, this motion is linear. This method also has several disadvantages: the aspheric surfaces are difficult to fabricate because they are not rotationally symmetric, and the effect on image quality can be unacceptable.

5. A bifocal or multifocal lens can be constructed such than some regions of the lens form a distant image and other regions form a close image. This method is particularly attractive for applications which only require two focus positions, and because no moving parts are required. Disadvantages of this method include lowered resolution and fabrication difficulties.

6. A liquid filled lens has been used in some applications requiring a variety of focus positions. The liquid is held between compliant thin windows that form the outer optical surfaces. As liquid is pumped into or out of the lens, the compliant walls change shape, causing a change in focal length of the device. This method has the advantages of having no moving optical parts and of the potential for quick adjustment times. This method has the disadvantages of a limited accommodation and all the troubles that come with the use of a liquid.

7. Liquid crystal lenses have been used in many applications requiring a quick adjustment in focal length. In a liquid crystal lens, the liquid crystal is placed inside of a lens-shaped cavity. When an electric field is applied to a liquid crystal, the molecules tend to align. Their uniaxial or biaxial symmetry creates a phase retarder. The liquid crystal lens is made without polarizers. Rather than create a quadratic phase variation, researchers have made liquid crystal Fresnel lenses. As voltage is applied to the liquid crystal, its index changes, causing a change in the focal length of the lens. This method has the advantages of having no moving parts, the potential for very fast adjustment speed, and maintaining the correct pupil position. This method has the disadvantage of having a limited accommodation, as well as having all the disadvantages of using a liquid crystal.

8. Adaptive optics are also often used in changing the phase profile of light. Adaptive optics are lenses or mirrors which change shape using a variety of actuator methods. This method has the advantage that a continuous adaptation can be provided. However, adaptive optics usually suffer from the disadvantages of being difficult to control; furthermore, they are a new technology and therefore tend to be expensive.

CONVERGENCE METHODS

A wide variety of convergence methods are also available. These methods include, in no particular order, the following:

1. Video centering
2. Translating the display
3. Tilting the entire assembly
4. Optical wedges in front of the eyes

1. Video centering achieves convergence by electronically moving the center of the scene away from the center of the display device. For example, when simulating the convergence of an object at infinity, the images will be moved towards the nose to create the desired convergence angle. This method has the advantage of having no moving parts and allowing quick convergence times. Its disadvantages include more complex electronics, rotation about the pupil, and the fact that the display must in effect be larger than what is required for any given convergence situation. Figure 4 shows a graphical representation of the video centering methodology.

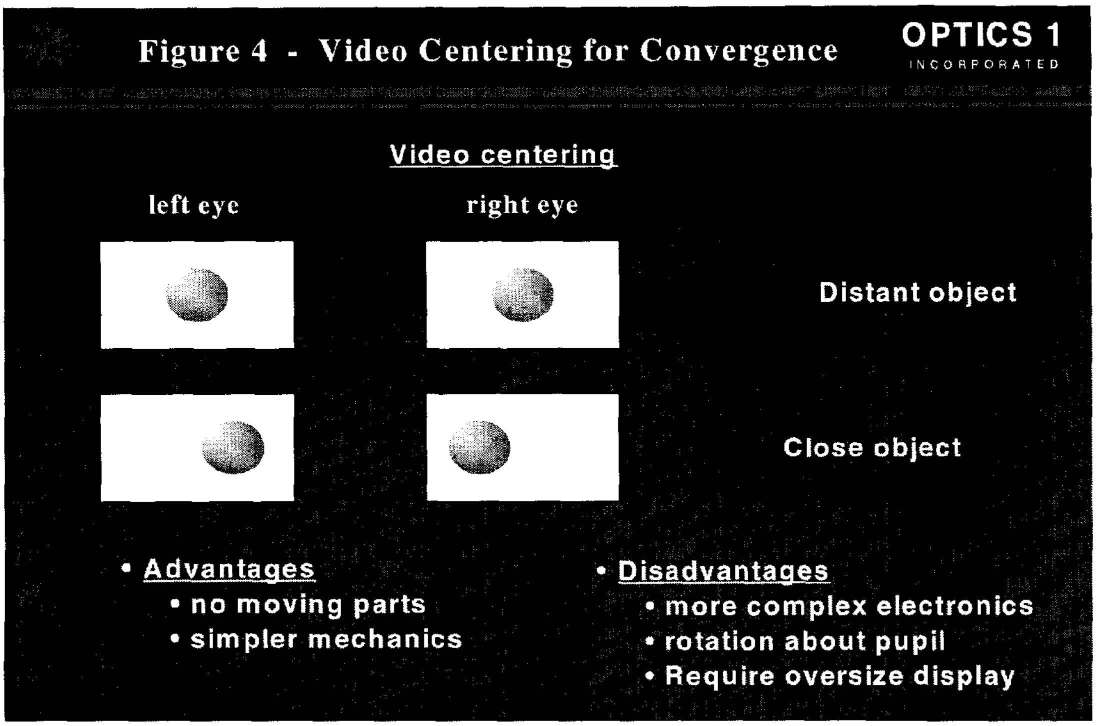


Figure 4

2. Convergence can also be achieved by translating the entire display devices towards the nose. This is often a problem as the electro-mechanical implementation may be difficult.

3. The entire viewing optics assembly including the optics and the display can be tilted to match the desired convergence angle. Ideally this tilt angle should be at about the eye pupil location so as to avoid vignetting or other bad optical effects. While this is a difficult implementation task, it correlates directly with the desired result, making it somewhat attractive.

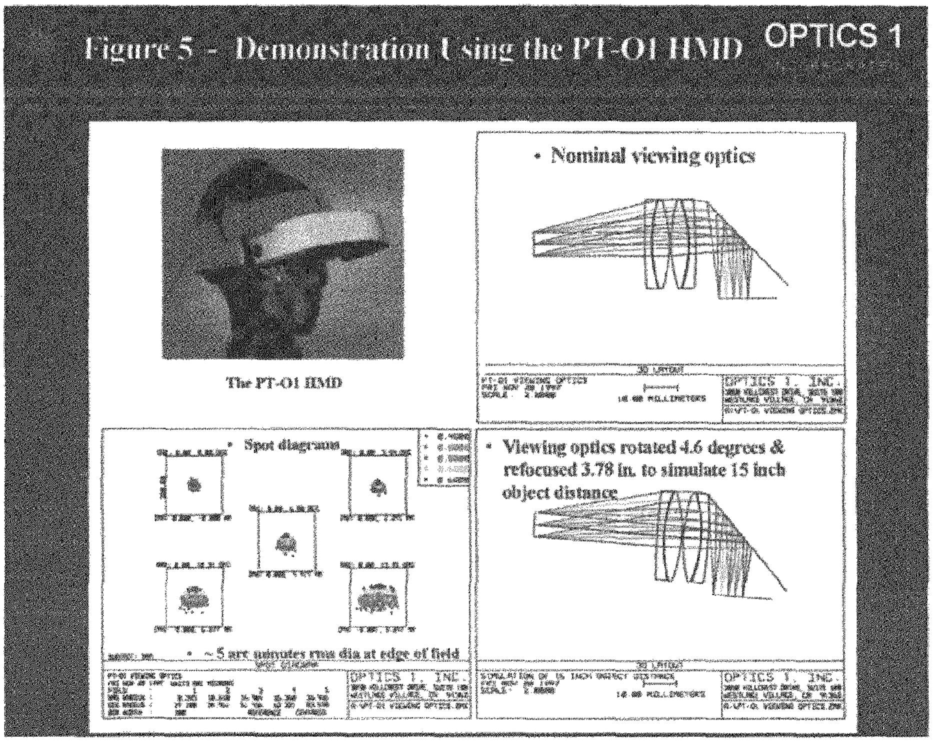
4. We can locate optical wedges in front of the eye so as to vary the magnitude of convergence presented to each eye. If two optical wedges or weak prisms are counter-rotated we can achieve a variable degree of convergence. The disadvantages include the mechanization complexity as well as lateral color or color fringing around objects. A liquid filled variable wedge is also feasible.

EXAMPLE OF A CANDIDATE IMPLEMENTATION

In order to give a realistic example of a viable implementation, we have modified our PT-O1 HMD product in order to allow for a rapid change in both accommodation and convergence from infinity to a distance of approximately 15 inches. This HMD is a commercial product used in video inspection, cinematography, and other professional areas. Its field of view is 27.5 degrees diagonal and thus not ideal for a simulation application, however we used it here due to its availability.

The convergence change was accomplished by rotating the viewing optics and display assemblies in front of each eye by approximately 4.6 degrees towards the nose, and the accommodation was accomplished by refocusing each of the viewing optics lens assemblies by 3.8 mm towards the LCD display device. As it was not possible to rotate the assemblies about the ideal eye pupil location, the performance is not ideal. However, it does demonstrate the feasibility and the overall performance of such an implementation.

Figure 5 shows the lens design for the HMD as well as its optical performance in the form of geometrical spot diagrams. We show that the imagery at the very corner of the field of view is in the order of 5 arc minutes rms blur diameter which is reasonable for this application. We also show the lens assembly and display device rotated towards the nose by 4.6 degrees.



SUMMARY AND CONCLUSIONS

The literature clearly shows the importance of providing the cues of accommodation and convergence in an HMD when used in a simulation environment. This is especially true when the user is in a simulated cockpit or similar environment where imagery of close objects must be simulated as well as imagery of objects at infinity and/or other distances.

We have shown the accommodation and convergence demands for a typical HMD as used in a simulation environment. It is important that the accommodation and convergence demands both be appropriately coupled. Eight different methods for implementation of a variable accommodation and 4 methods for variable convergence in an HMD were presented. The different methods differ from one another in complexity, performance, and other factors. Additional work will be directed towards identifying the optimum system for implementation.

ACKNOWLEDGEMENTS

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